Cross sectional echocardiographic assessment of left ventricular volume and ejection fraction in patients with tetralogy of Fallot
Comparison with biplane angiographic measurements

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SUMMARY To evaluate the usefulness and accuracy of calculating left ventricular volume and ejection fraction from cross sectional echocardiograms in patients with tetralogy of Fallot, 28 patients were studied within 24 hours of cineangiography. Indexed end diastolic and end systolic volumes were calculated from three different paired echocardiographic projections: (*a*) the two and four chamber views from the apical impulse window, (*b*) the parasternal long axis view and the sub-xiphoid long axis view, and (*c*) the four chamber view and short axis precordial views at mitral and papillary muscle level. Volumes were calculated in five different ways using three different algorithms (area length, Simpson's rule, the Parisi formula). The results were compared with data obtained from biplane angiograms using Graham's formula. The correlation varied with the algorithm used: the best results were obtained with the area length method using the parasternal long axis view and the sub-xiphoid view. The correlation was less accurate for the ejection fraction. The second best correlation was obtained with the area length method using the two and four chamber apical views; the other correlations were less satisfactory.

Thus these results show that left ventricular volumes can be accurately assessed by cross sectional echocardiography in children with tetralogy of Fallot and that the ejection fraction can be satisfactorily estimated. The results depend on careful gain setting and precise demonstration of the left ventricular endocardium, which is best seen in the sub-xiphoid and long axis views.

Determination of left ventricular volume and ejection fraction in children has relied mostly on left ventricular angiography which remains the gold standard.[1–4] Real time echocardiography became available a few years ago for assessing cardiac malformations in adults[5–7] and in children,[8–10] and more recently calculation of left[11–13] and right ventricular volumes[14 15] and ejection fraction became possible with this method.[16–18] Accurate assessment of left ventricular volumes using cross sectional echocardiography in experimental animals[19–22] and in adult patients with valvular or coronary artery disease has been reported.[12 23 24] Some preliminary studies of children with various congenital heart defects have also been reported.[13 25] Because these defects alter the position and loading condition of the left ventricle the ideal cross sections and algorithms to be used may vary from one type of heart disease to another. The cross sectional echocardiographic apical views have so far been found to be the best views for estimating left ventricular volumes and ejection fraction in children and adults.[12 13 24] These views are, however, rather difficult to obtain in some cardiac malformations and in the very sick and anxious child. More recently, short axis views combined with a four chamber apical view were favoured for evaluating cardiac function.[17 18 25]

In this study we focused our attention on the left ventricle in patients with tetralogy of Fallot because left ventricular volume and function are of particular interest and importance in the postoperative outcome in these patients.[3 26] Furthermore, we chose a group

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of patients that was homogeneous with regard to cardiac position in the chest and loading condition of the left ventricle.

Patients and methods

Twenty eight children (12 girls, 16 boys; age range 1 month to 14 years (mean age 6 years 11 months); mean weight 18·1 kg, range 4·23–43·5 kg) with tetralogy of Fallot who had undergone preoperative cardiac catheterisation with good left ventricular angiograms and good cross sectional echocardiograms were included in the comparative evaluation of left ventricular volumes and ejection fraction. One of these children also had significant mitral incompetence.

ECHOCARDIOGRAPHY

Real time echocardiography was performed 12 to 24 hours before angiography. A mechanical sector scanner (Advanced Technical Laboratories Mark 5) was used with either a 3 MHz or 5 MHz transducer. Apical long axis and parasternal long axis and short axis views and sub-xiphoid long and short axis views were recorded as previously described.[6 8–10 13] The patients were examined in the left lateral decubitus position for parasternal and apical views and in the supine position with bent knees for the sub-xiphoid views.

Images and calibrations were traced with the aid of a microprocessor controlled light pen system (Fig. 1) on a digitising table, the traced cavity being displayed directly on the video screen. This system was connected to a minicomputer (Cardio 80 system). End diastole was defined as the frame at which the reference electrocardiogram reached either the trough of the Q wave or the upstroke of the R wave when no Q wave was present. End systole was defined as the frame at which the reference electrocardiogram reached the end of the T wave or the smallest left ventricular silhouette. The papillary muscles were excluded from the outline tracing in the short axis views only.

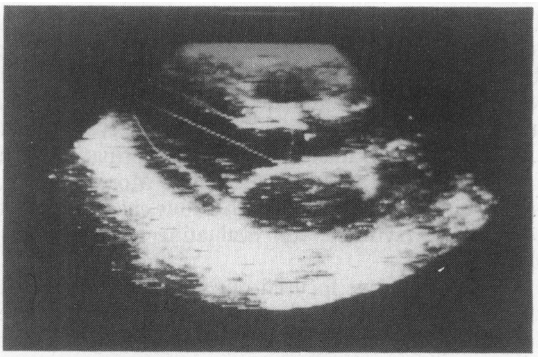

Fig. 1 *Cross sectional echocardiogram with light pen tracing of the left ventricle in a long axis projection.*

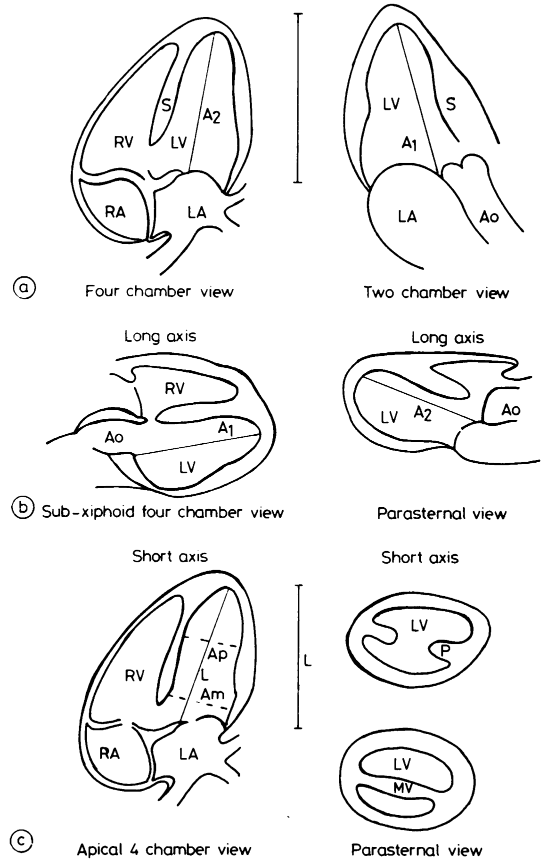

Fig. 2 *Diagram of the three different models used for volume calculations in five different algorithms: (a) apical four and two chamber views; (b) sub-xiphoid four chamber and parasternal long axis views—volumes in both models are calculated using the area length method:* $V = \frac{8A_1 \cdot A_2}{3\pi L}$

and Simpson's rule: $V = \frac{\pi}{4} \sum_{i=1}^{n} ai \; bi \; \frac{L}{n}$;

(c) apical four chamber and parasternal short axis views. The volume is calculated using the Parisi formula (modified Simpson's rule):

$$V = (Am) \frac{L}{3} + \frac{(Am + Ap)}{2} \frac{L}{3} + \frac{1}{3}(Ap) \frac{L}{3}.$$

A_1, A_2, planimetered areas: ai, bi, short axis diameters; L, length of common LV axis; V, volume; Am, area at mitral valve level; Ap, area at papillary muscular level; RA, right atrium; RV, right ventricle; LA, left atrium; LV, left ventricle; S, septum; P, papillary muscle; MV, mitral valve; Ao, aorta.

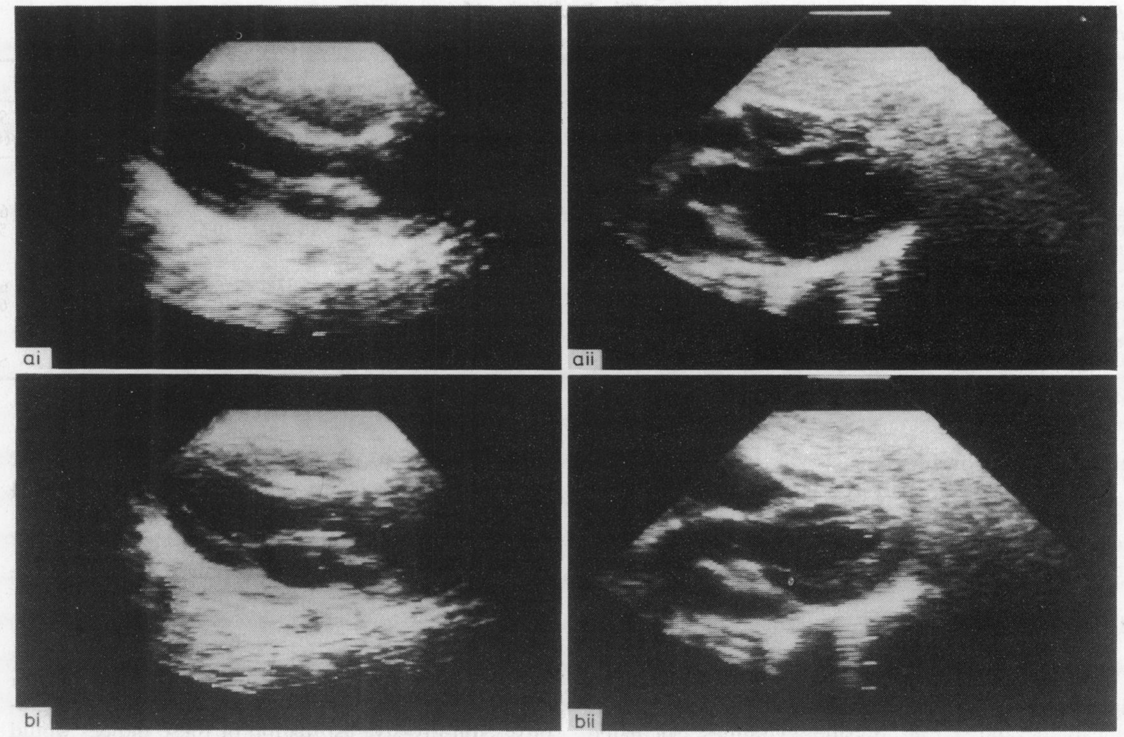

Fig. 3 *Cross sectional echocardiographic orthogonal (a) end diastolic and (b) end systolic projections of the left ventricle obtained in the (i) parasternal long axis view and the (ii), sub-xiphoid long axis view.*

Volume calculations

The Cardio 80 system allowed the analysis of the end systolic and end diastolic areas and calculated the corresponding volumes using five algorithms based on three geometric models (Fig. 2); one tracing could not be used for more than one algorithm. Thus for each new algorithm chosen the end diastolic and end systolic silhouettes had to be retraced. For each volume and ejection fraction of one particular algorithm two to five individual tracings were made and the corresponding calculations averaged.

Simpson's rule was applied to two paired sections of the diagram (Fig. 2a and b): the two and four chamber apical views and the sub-xiphoid and parasternal long axis views. Both are combinations of two perpendicular planes. This algorithm assumed the volume of the ventricle to be the sum of small cylinders and a truncated ellipse.

The biplane area length method was applied to the same sections as described under Simpson's rule. Fig. 3 shows the real time images using the sub-xiphoid and the parasternal long axis projections at end diastole and end systole.

A modified Simpson's rule (the Parisi formula) was used for the calculation of left ventricular volumes using the four chamber apical view and parasternal short axis views at mitral and papillary muscle level (Fig. 2c).

CINEANGIOCARDIOGRAPHY

During routine catheterisation under light sedation (pethidine, chlorpromazine, promethazine) left ventricular biplane cineangiocardiograms were obtained in the left and right oblique position at a 90° angle at 50 or 75 frames/s. Special care was taken to avoid extrasystoles and to assure an adequate technical quality for calculating angiographic volumes. A sphere of 6 cm diameter was filmed at the position of the heart in both projections to correct for linear magnification. End diastolic and end systolic frames were used to calculate left ventricular end diastolic and end systolic volumes and the ejection fractions using the area length method[27] with the modified regression equation of Graham *et al.*[28]

STATISTICAL ANALYSIS

Left ventricular end diastolic and end systolic volumes and the ejection fraction obtained from cross sectional echocardiograms with each algorithm were compared with biplane cineangiocardiographic vol-

Table *Correlation between angiographically and echocardiographically determined left ventricular volumes and ejection fraction using three geometric models and five different algorithms*

Geometric model and algorithm	*n*	*End diastolic volume*				*End systolic volume*				*Ejection fraction*			
		r	*Slope*	*Intercept*	*SEE (ml)*	*r*	*Slope*	*Intercept*	*SEE (ml)*	*r*	*Slope*	*Intercept*	*SEE (ml)*
Two and four chamber apical views													
Area length method	22	0·87	0·81	13·64	14·94	0·93	0·92	3·58	7·89	0·72	0·82	7·71	6·23
Simpson's rule	19	0·61	0·83	16·6	18·58	0·60	0·91	5·72	10·03	0·62	0·43	32·86	5·11
Parasternal and sub-xiphoid long axis view													
Area length method	28	0·95	0·95	3·32	10·79	0·97	1·01	1·93	5·37	0·70	0·81	7·13	6·56
Simpson's rule	25	0·87	0·91	7·72	12·64	0·87	1·01	3·50	6·17	0·55	0·51	24·52	6·69
Four chamber view and 2 short axis views													
Parisi formula	25	0·68	0·74	31·03	24·79	0·84	0·85	13·31	10·92	0·64	0·71	11·08	6·51

SEE, standard error of the estimate.

umes and ejection fractions.

Linear regression analysis was performed; standard errors of the estimate (SEE) and the correlation coefficients (r) were calculated for the number of cases studied.

Results

The Table shows the correlation of volume determinations by cross sectional echocardiography and cineangiography. End diastolic volumes calculated from cineangiograms ranged from 28·7 to 175·7 ml, whereas systolic volumes ranged between 10·0 and 113·3 ml. Echocardiographically determined volumes varied with the algorithm used. The two geometric models using orthogonal views either from the apical window or the combined parasternal and sub-xiphoid long axis views provided good results using the area length method. The Simpson's rule algorithm was less satisfactory in this study. There were significant differences between volume calculations by the area length method and Simpson's rule (Table).

Fig. 4 shows the results for the two geometric models using the area length algorithm, cross sectional echocardiographic volumes and ejection fraction being plotted against angiographic values. Cross sectional echocardiography tends to underestimate slightly but significantly ($p<0·01$) the cine angiographically determined values. The combined orthogonal cross sectional measurements in the sub-xiphoid and the parasternal long axis views (Fig. 4 d–f) in this study proved to be superior to those in the apical two and four chamber views (Fig. 4 a–c) in determining volume and ejection fraction. The modified Simpson's rule (the Parisi formula) using the four chamber apical view and parasternal short axis views at the mitral and papillary muscle level showed a large scatter for all values (Table). In this projection the identification of the endocardial border is difficult and cannot always be obtained in children. Correlation between the values obtained by cross sectional echocardiography and cineangiography are show the Table and Fig. 4 for end diastolic and end syst volumes as well as ejection fractions.

Discussion

Until now the determination of left ventricular volumes and ejection fraction has relied on cineangiography. Non-invasive estimation of these indices would be useful so that repeated measurements could be taken without catheterisation. Many attempts have been made to determine the accuracy of the echocardiography in assessing ventricular function, first by M mode[29–31] and more recently by cross sectional sector scanning.[19–22] These reports have shown satisfactory correlation between the cross sectional echocardiographic assessment of left ventricular volumes and function indices and angiocardiographically calculated values.[11 12 16–18] Most of the studies were carried out either in animals[19–22] or in adults with coronary and valvular heart disease.[17 23 32 33] Only very few studies deal with children with a variety of congenital cardiac malformations.[13 14 25]

Various mathematical formulas for the calculation of volume from cross sectional echocardiograms have been used and compared with angiographically obtained values.[19 20] Whatever the formula used, considerable variations have been noted between results of these two methods.[12 18 33] The causes of the variability found in several recent studies have been more extensively investigated by some researchers.[32 34 35] The factors found to influence the accuracy of measurements include technical characteristics of a machine and the scan head, problems with axial, lateral, and cross plane resolution, tissue interactions, limited sampling rate, gain setting, insufficient dynamic range of available display devices, and

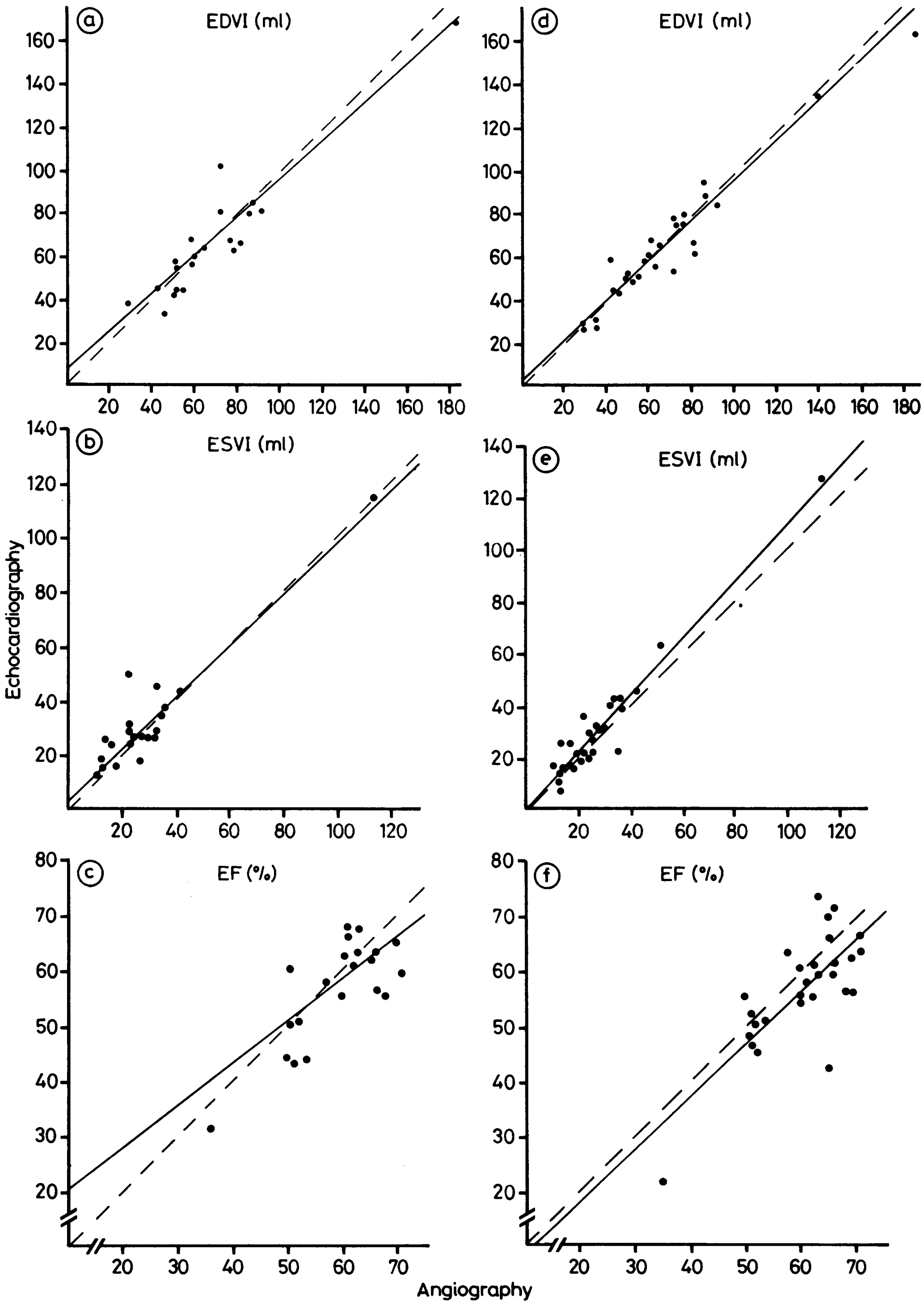

Fig. 4 *Indexed biplane angiographic end diastolic (EDVI) and end systolic (ESVI) volumes and ejection fraction plotted against indexed volumes and ejection fractions calculated with the area length method from cross sectional echocardiograms in (a–c) the two and four chamber apical views and (d–f) the parasternal and orthogonal sub-xiphoid long axis views of the left ventricle.*

artefacts related to the video recording system. In addition, factors relating to the patient himself—that is, the size of the echo window, changes in cardiac geometry, the patient's cooperation, and uncertainty of spatial orientation in three dimensions—contribute greatly to differences in quantitative evaluations.[33-35] Such considerations are especially important in children. Changes in cardiac geometry are pronounced in patients with different cardiac malformations and abnormal loading conditions,[36] and this is an important consideration in patients with tetralogy of Fallot. In this malformation the hypertrophied and dilated right ventricle lies more anteriorly and pushes the left ventricle upwards and backwards, thus changing the intrathoracic and intracardiac geometry. The aorta is displaced anteriorly and overrides the ventricular septal defect and the septum.

Standard cross sectional echocardiographic projections of these hearts are more difficult to obtain; some may be impossible, the echo window frequently being small in these children. The apical window is displaced; thus the two and four chamber views are less reproducible and sometimes distorted. The identification of the endocardium can become extremely difficult and needs continuous gain setting. Short axis views of the left ventricle are also displaced, distorted, and more difficult to define. Volume calculations of one or other projection can therefore become difficult, uncertain, less reproducible, or even unrealistic.

We tried to find the most simple and reliable projection of the left ventricle in two orthogonal cross sections for volume calculations in patients with tetralogy of Fallot. The sub-xiphoid long axis view and a low parasternal long axis view appear to be easily reproducible perpendicular planes in these patients, and the endocardium is well outlined. These two planes appear, therefore, to be the best cross sections for volume calculation.

Correlation coefficients varied with the algorithm and the geometric model used (Table). Compared with published data, the correlations were generally comparable but weaker (Fig. 4). Echocardiographic volume calculations underestimated angiographic volumes only slightly but less than in other reports.[12 13 25] Being aware of the technical difficulties in defining the left ventricular endocardium, we used a rather low gain setting for the cross sectional echocardiogram, and also repeatedly changed the light setting at the video screen before each tracing. Thus the left ventricular area probably became larger than in previous studies. Nevertheless, there was quite a wide variability between individual calculations. The correlations between echocardiographic and angiographic data improved when several individual volume calculations for different cardiac cycles were averaged. For the area length method, in general, a mean of five measurements was used, whereas for the Simpson's rule only two, sometimes three, cardiac cycles could be averaged. This might have contributed to the fact that Simpson's rule correlated less well in the present study. Also, the fact that the area length method was used for calculating angiographic volumes[31 32] may contribute to a better correlation with real time echocardiography when the same algorithm is used.

The rather wide scatter of individual measurements, however, stresses the fact that imaging of the left ventricle is significantly more difficult in patients with tetralogy of Fallot than in children with cardiac malformations with left ventricular volume overload. In different cardiac malformations the intrathoracic position and the shape of the ventricles vary as well as the loading conditions; it therefore becomes necessary to find a simple method of easily assessing the left ventricle in two orthogonal planes. An "ideal" orthogonal plane might not always prove to be the same projection in various cardiac lesions. In right ventricular pressure and volume overload combined sub-xiphoid and parasternal long axis views proved to be the most useful approach considering the results of this study. These two projections can be obtained easily and repeatedly with good reproducibility. Whether these projections can, however, also be used for other congenital and acquired malformations needs further investigation and careful assessment.

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